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Modelling of a High Temperature PEM Fuel Cell Stack Using Electrochemical Impedance Spectroscopy

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Motivation

In designing and controlling fuel cell systems it is advantageous having models predicting the behavior of the fuel cells in steady-state as well as in dynamic operation. This work examines the use of electro-chemical impedance spectroscopy (EIS) for characterizing and developing a model for a high temperature PEM (HTPEM) fuel cell stack. A Labview virtual interface has been developed to perform the signal generation and acquisition which is needed to perform EIS. The typical output of an EIS measurement on a fuel cell, is a Nyquist plot, which shows the imaginary and real part of the impedance of the measured object. A typical Nyquist plot of a typical equivalent electric circuit of fuel cell is shown in figure 1.

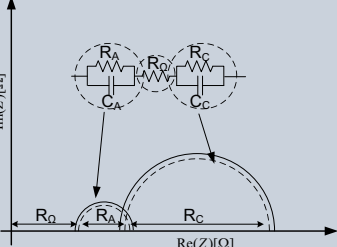


Figure 1: Nyquist plot of the shown electrical circuit. The subscript A referring to the fuel cell anode, C to the cathode, and Ω to the ohmic losses of the fuel cell.

The electrical connections of the fuel cell stack setup is shown in figure 2. The fuel cell voltages can be measured in different places to examine the impact of fuel cell stacking.

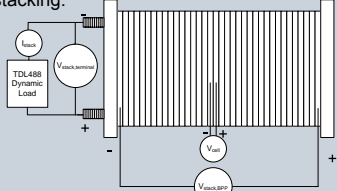


Figure 2: The stack voltage is measured on the stack terminals, but can also be taken directly from the bipolar plates.

The developed software is able to include multiple of the simultaneously measured current and voltages in the signal conditioning using the same stack current.

HTPEM Fuel Cell Stack Electrochemical Impedance Spectroscopy

The fuel cell stack tested in this work is a 65 cell 1 kW HTPEM fuel cell stack using a polybenzimidazole (PBI) membrane doped with phosphoric acid to increase the proton conductive abilities of the membrane. The HTPEM fuel cell stack is fuelled with pure hydrogen in a dead-end anode configuration at a constant pressure of 0.2 bar. The air to the cathode is supplied by a low power axial blower, which also is used to control the stack temperature. The temperature control is realized by a feed forward of the current and a feedback of the measured stack temperature. Figure 3 shows the fuel cell system setup, and components in the system.

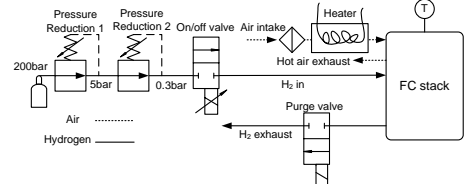


Figure 3: System diagram of the experimental setup for the fuel cell stack.

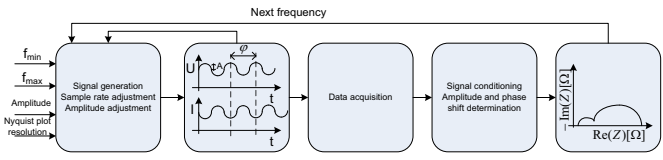


Figure 4: Block diagram of the Labview program structure.

The Labview based program controls the I/O from a PCI 6259 Multifunction DAQ. The board controls a 16 bit 0-10V analog output signal as a current set point for the TDI Power RBL 488-100-300-2000 dynamic load module. The analog signal is an offset DC signal with a superimposed sine wave of varying frequencies. The data acquisition and signal conditioning is visualized in figure 4. For the EIS measurements, a frequency range is specified which is logarithmically divided, depending on the desired resolution of the final output. The desired RMS amplitude of the measured voltage can also be specified. In the results presented here only measurements using the system in potentiostatic mode are shown, i.e. specifying the amplitude of the voltage signal. As shown in figure 2, it is also possible to measure impedance of a single cell voltage during the measurement, due to large common mode voltage differences in the middle of the stack, this signal is measured through a unity gain differential amplifier.

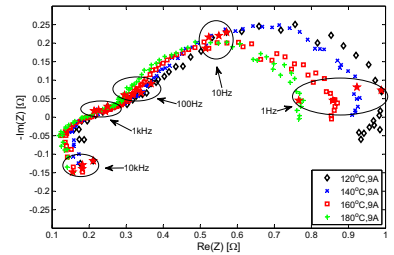


Figure 5: Nyquist plot of fuel cell stack impedance at different temperatures, using Labview based program. DC current offset is 9 A.

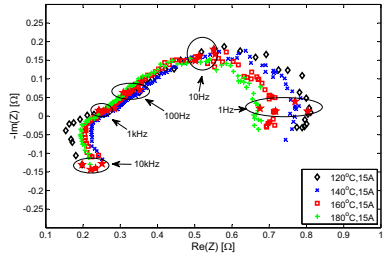


Figure 6: Nyquist plot of fuel cell stack impedance at different temperatures, using Labview based program. DC current offset is 15 A.

Nyquist plots made using measurements of the presented system are shown in figure 5 and 6. In figure 5 and 6 Nyquist plots of the fuel cell stack impedance is shown at a 9 and 15 A DC offset current and at different stack temperatures. The choice of the DC current offsets is within the linear operating point on stack polarization curve. The measured Nyquist plots show similar behavior to the equivalent circuit model shown in figure 1, with a large cathode semi circle in the low frequency range, and a small anode semi circle in the high frequency range. The measurements show that both the real and imaginary parts decrease with increasing temperatures, i.e. the electrical dynamic performance is better at higher temperatures. This is also expected, while the speed of the chemical processes occurring typically speed up at higher temperatures. In the case of a fuel cell stack impedance compared to a single cell impedance, the stack consists of many series connected fuel cells with varying temperatures and therefore also impedances. This could be one explanation of why there is not a clear distinction between the two semi circles in the measurements. results from these measurements are much similar.

Modelling

The impedance of a stack of series connected fuel cells resemble that of a single cell, although the different temperatures can make it difficult to determine the exact sizes of the cathode and anode equivalent circuits. Figure 7 shows measurements on the same system made with a Gamry FC360 Fuel Cell Monitor to verify the results from the developed Labview program.

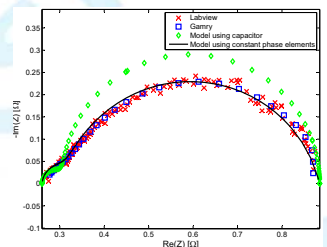


Figure 7: Comparison of Nyquist plots created using different models and different experimental equipment.

Using an equivalent model for the entire stack, as the one shown in figure 1, with $R_A=0.045\Omega$, $C_A=0.05F$, $R_C=0.58\Omega$, $C_C=0.3F$, and $R_0=0.26\Omega$, yields the Nyquist also shown in figure 7. It is seen that the plot has a too high capacitive impact compared to the experimental results. The fuel cells do in this case not behave strictly as standard electrical components, so to get a better model representation the cathode capacitor is substituted by a constant phase element with the transfer function: $C_C(s)=1/(C_C(j\omega)^P)$. The result is using the same values for resistances and capacitances as for the purely capacitor based model, with $P=0.85$. The resultant model predicts the behaviour of the fuel cells much better.

Conclusions

The experimental results presented suggest that the developed Labview software is capable of making a frequency scan of the fuel cell current and voltage, resulting in a Nyquist plot showing the impedance of the fuel cell stack. A simple equivalent circuit model can be used to simulate the fuel cell stack behaviour, but the impedance is non-linear and depends on other variables such as for example temperature.

Future work with this fuel cell stack includes measuring the impedance at different hydrogen pressures and cathode stoichiometries. To further characterize the anode part of the fuel cell stack, measurements with different CO concentrations in the supplied hydrogen should be made. Single cell measurements should also be carried out to analyze the impact on the impedance when stacking the fuel cells.